A "Linkless" Architecture for Large-Scale MANETs

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Outline

- What ails the current architecture?
- Which part of the system should we fix?
  - Insights from "symptotic" analysis
- How should we fix it?
  - Ideas and architecture for the next generation

What ails the current architecture?

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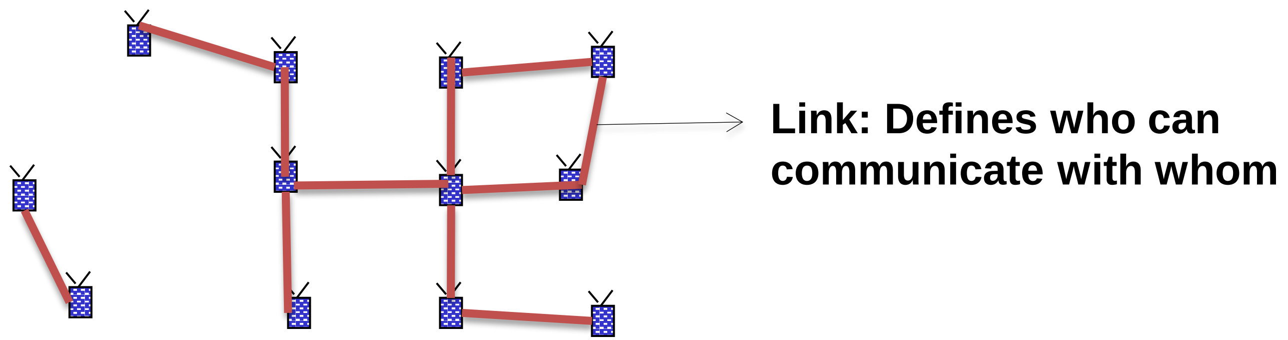
Links are everywhere



- Network layer
  - OLSR: Optimized *link* state routing
  - Multi-*path* routing, *link* reversal routing, *link* cost/stability
  - Topology control (Topology = union of *links*)
- MAC/*Link* layer
  - *Link* activation/scheduling, RTS-CTS-DATA-ACK over a *link*
- PHY layer
  - *Link* budget/margin

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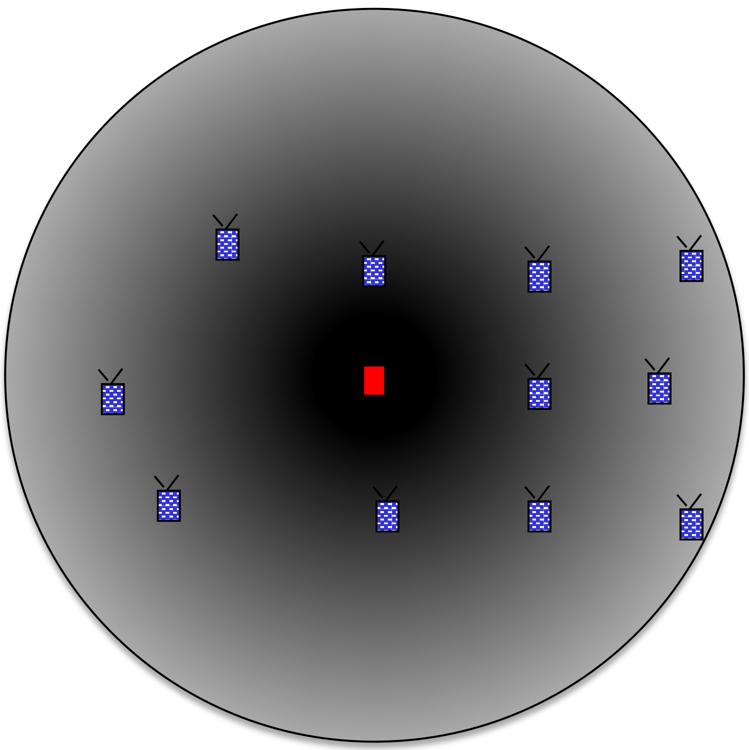
But a MANET has no Links



Instead, a complex tradeoff space

RATE

RANGE

Power
Modulation
Coding
Frequency
Interference
Antennas
ETC.

COST

ERRORS

Using a link to represent above has resulted in several inefficiencies

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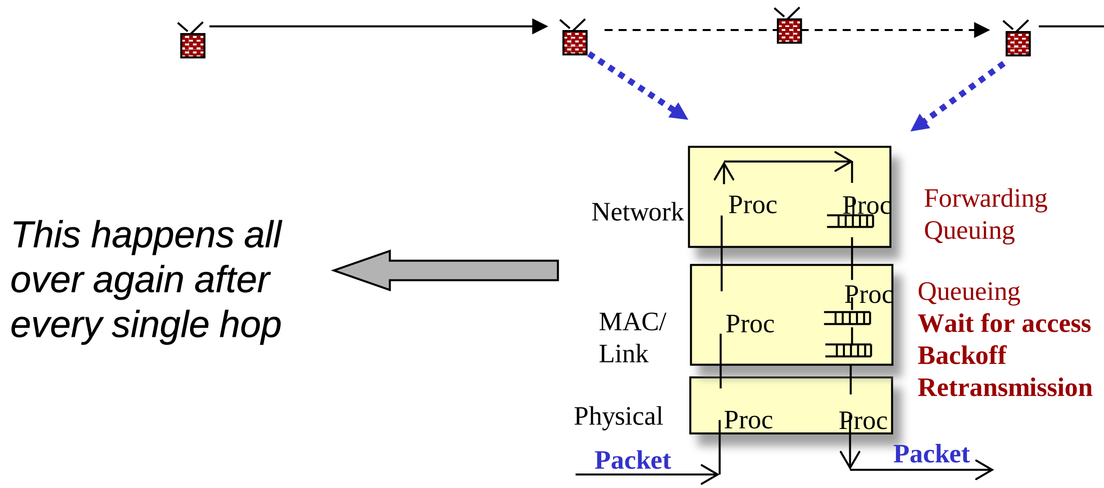
Per-link operations

- Packet relaying in today's MANETs is link/hop centric

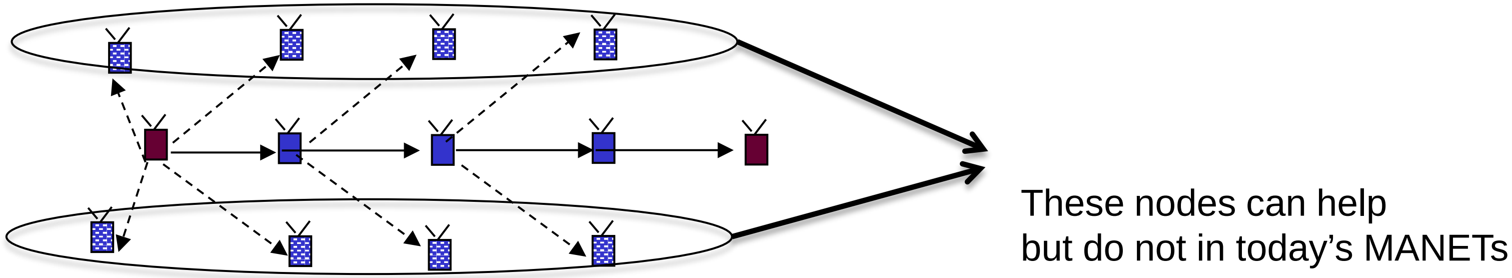
- Nodes re-process, re-queue and *re-contend* afresh at every single hop along the way to the destination



- A packet spends a vast majority of its transit time *inside* a node (at the MAC/Network layer), rather than on the air

Uncooperative Operations

- A link-based architecture discourages cooperation from nodes not part of the “link”
  - Many nodes receive a piece of information but *offer no help* in forwarding it, since they are not on the *link*
  - This is a waste of the *wireless broadcast advantage*
  - Thus, *session throughput* is limited by *link throughput*



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Other Consequences

- Need to track topology or destination-based trees
  - Hard to characterize (up/down/cost) a wireless “link”
  - Mobility and other dynamics
  - Overhead
  - Loss of control information means you fail even when routes exist

- Leads to unicast bias
  - A sequence of links is a *unicast* path
  - Most works analyze/simulate performance with unicast
  - *But military traffic is overwhelmingly multicast or broadcast!*

- *… and other such inefficiencies…*

R. Ramanathan, “Challenges: A Radically New Architecture for Next Generation Mobile Ad Hoc Networks”, *Proc. ACM MOBICOM 2005*

Which part of the system should we fix?

Insights from “Symptotics”

Symptotics

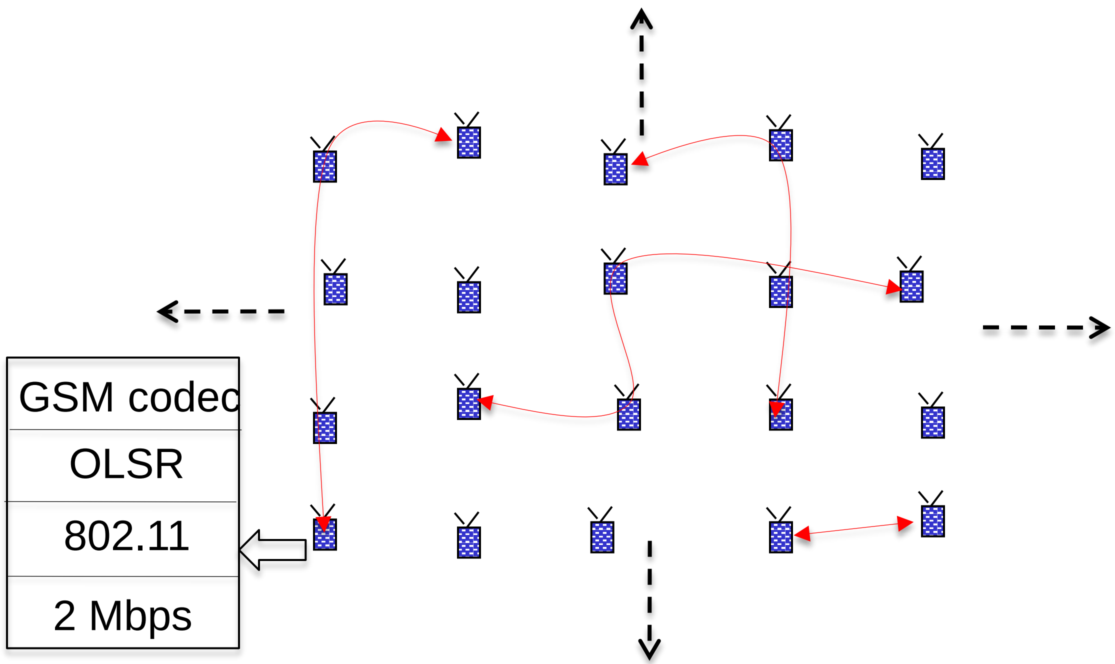
- A framework for non-asymptotic *real-world* network analysis
  - Asymptotic analysis: *Network X does not scale (e.g. C = O(1/√N))*
  - Symptotic analysis: *Network X with parameter vector P scales to 450 nodes*
  - Real-world protocol overhead and effects at each layer
  - Bottleneck phenomena, traffic types (unicast, multicast, broadcast)
  - Approximate: processing, queuing, errors etc. not modeled

- Symptotic scalability: Number of nodes beyond which the residual capacity of at least one node is non-positive

- Have derived 25+ symptotic scalability models for combinations of topologies, traffic, protocols
  - Validated a subset using simulations
  - Performed impact analysis: *which system parameter to "upgrade"?*

R. Ramanathan, A. Samanta, T. La Porta, "Symptotics: A Framework for Analyzing Real-World Wireless Networks, *Proc. of ACM PE-WASUN, Oct. 2012*

Example Scenario



A military "unit" moving in a rough grid formation

VoIP calls random distributed, 20% activation

OLSR (0.2 LSUs/sec/node)
802.11 DCF

2 Mbps raw, single transceiver

How many nodes can I deploy *roughly?*

If I want to scale to more nodes, what helps most? Reducing routing overhead? Increasing radio rate? Reducing load by compression? Changing the MAC protocol?

ROM Scalability Example

Model as degree-4 grid topology* with uniform random traffic

Symptotic Scalability with baseline parameters: 140 nodes

Reduce routing overhead by 10X:	154 nodes	1.1x
Reduce routing overhead to ZERO:	156 nodes	1.1x
Increase radio rate** by 5X:	1483 nodes	10.6x
Reduce packet size & rate by 2X :	651 nodes	4.6x
Ideal (maximal) load balancing:	472 nodes	3.4x
<u>Idealized</u> TDMA instead of 802.11:	373 nodes	2.7x

Change Impact Value

CIV(p, α)

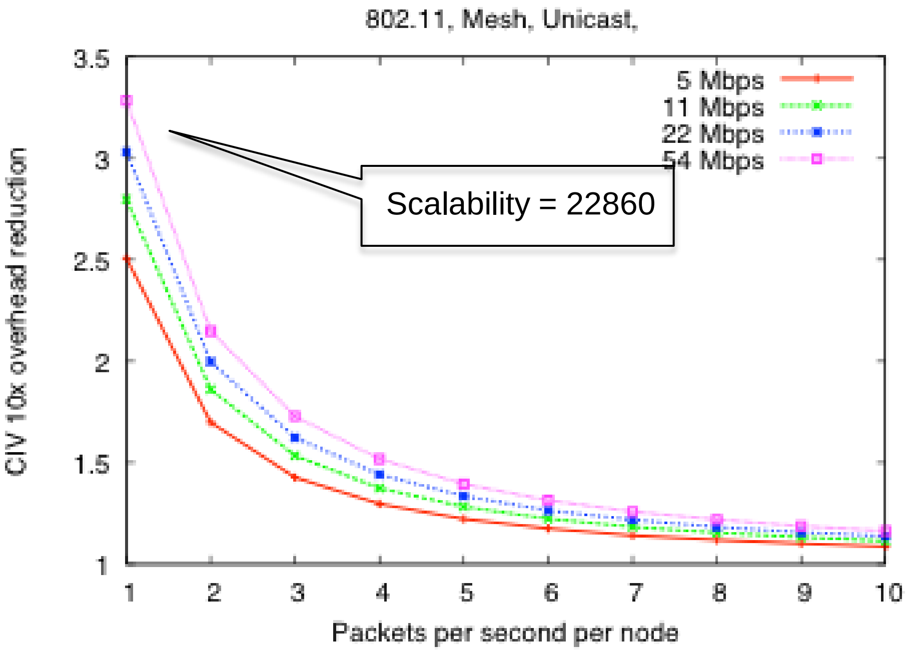
“Impact”

5X radio rate + load balancing + TDMA: 8525 nodes

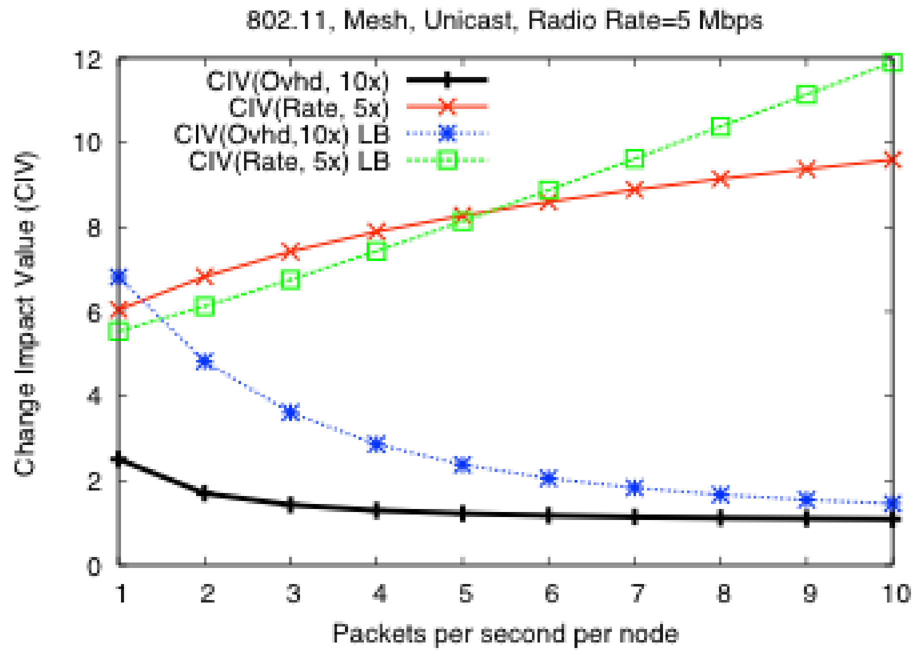
* Accommodates link state changes with frequency <= 1 per 5 secs/node
**Resultant range reduction not captured

Impact Analysis

Routing overhead impact vs load, rate, α=10



Comparing impacts of various parameters
LB = Load Balancing



- Impact of routing overhead on scalability
  - Increases with increasing radio rate and decreasing load – *but that is the happy case!*
  - Is significantly higher when load balancing employed
  - Is better felt if we first increase the “inherent” scalability

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Architectural Implications

- Provide higher capacity to higher layers
  - Multiple transceivers and channels
  - PHY layers that provide higher “effective” capacity for same raw rate
  - Higher raw transmission rate
- Reduce latency so it is not the bottleneck
  - Important because higher raw rate => higher frequencies => shorter transmission range => more relaying
- Highly efficient yet robust, adaptive and simple MAC
- Balance load to eliminate bottlenecks

Radically re-architect the bottom three layers of the stack

Architectural Elements

Cooperative Transport

Cut-through Relaying

Sync-less TDMA

Cooperative Communication

Un-cooperative

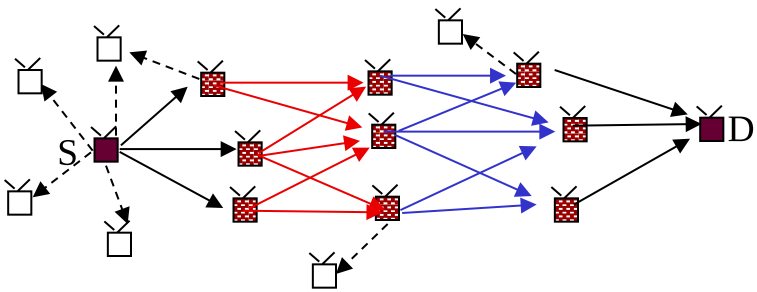
Cooperative

- Near-simultaneous transmission of information by multiple senders with an intent to combine at receiver(s)
  - Cooperative Diversity
  - Distributed Beamforming
  - Distibuted/Virtual MIMO
  - Tremendous advances in the last few years

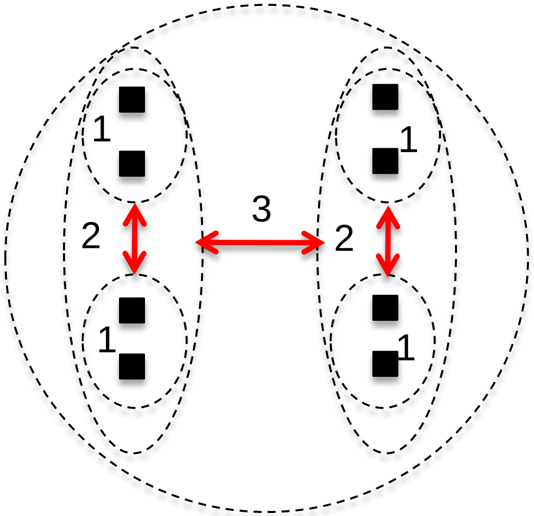
Cooperative Communications for MANETs

- Extend existing cooperative diversity work to *multi-hopping*

- *Stages* rather than *links*
- *Corridor/Conduit* rather than *path*



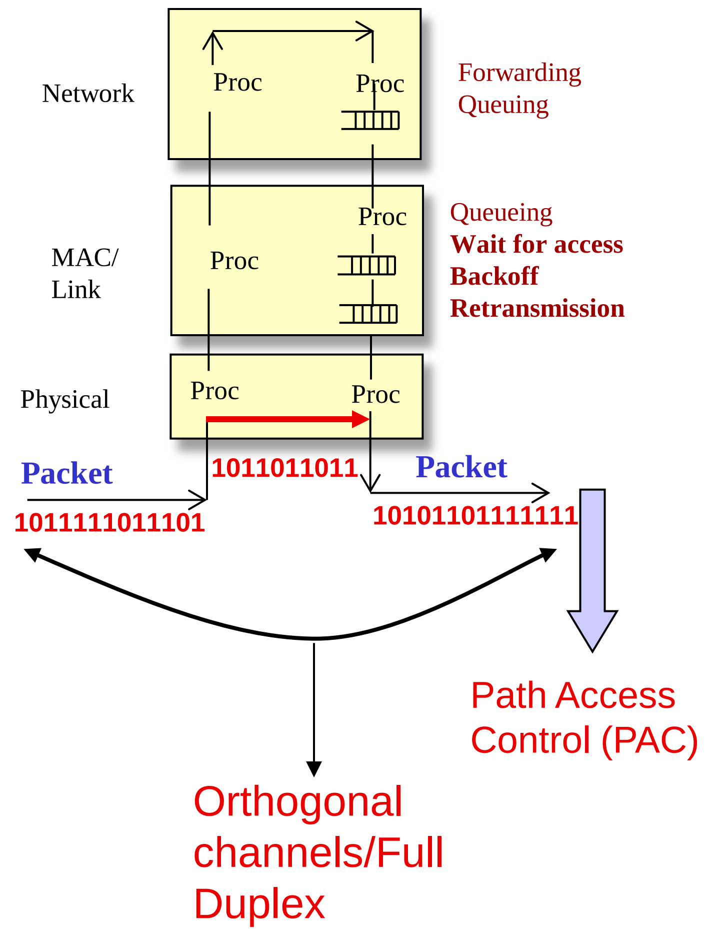
- Benefits
  - Higher path capacities or lower energy consumption possible due to increased SNR at each stage
  - Highly robust paths, especially in dense configurations
  - Protection against network partitioning
  - Theoretical and systems work has clearly demonstrated capacity gains



T. R. Halford and K. M. Chugg, "Barrage relay networks," in *Proc. Inform. Theory and Apps. Workshop*, La Jolla, CA, February 2010
A. Scaglione, D. L. Goeckel, and J. N. Laneman, "Cooperative communications in mobile ad hoc networks," *IEEE Signal Processing Mag.*, vol. 23, pp. 18–29, September 2006

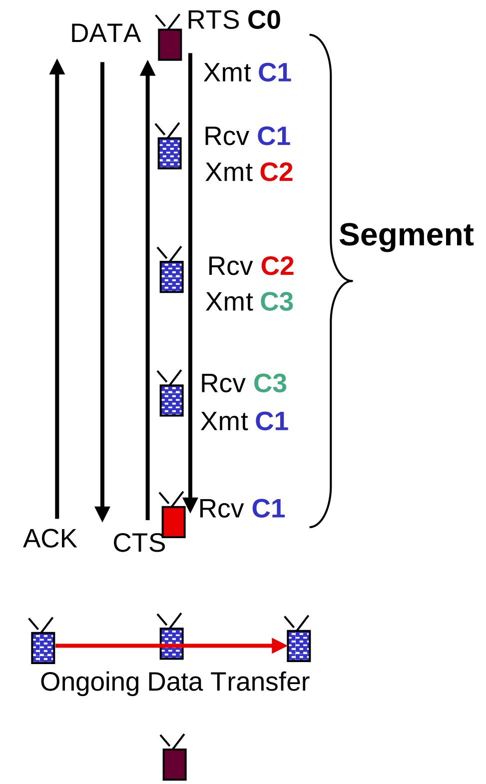
Cut-through Relaying

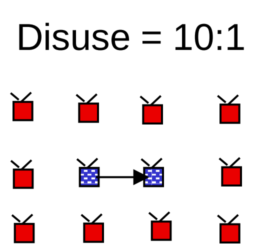
- Physical-layer relaying
  - Forward the packet without going up and down the stack
  - Couple the transmit chain to the receive chain
- Pipelining
  - Re-transmit without waiting for the entire packet to arrive
- Floor acquired before packet enters relay node
  - Source acquires the floor for multiple hops, ideally all the way to the destination

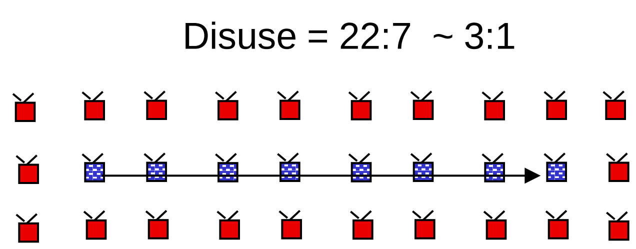


Path Access Control

- General idea: don't exit out of physical layer after each hop, keep going as far as you can
- Simple <u>example</u>: Path-Oriented CSMA/CA
  - RCDA scoped over a cut-through relayed *path*
- Segment duration is very small (~ link latency) due to phy-layer relaying and no waiting for access
- Cut-through + PAC helps also increases capacity
  - Intuition: lower spatial "disuse", ie, number of nodes blocked from sending

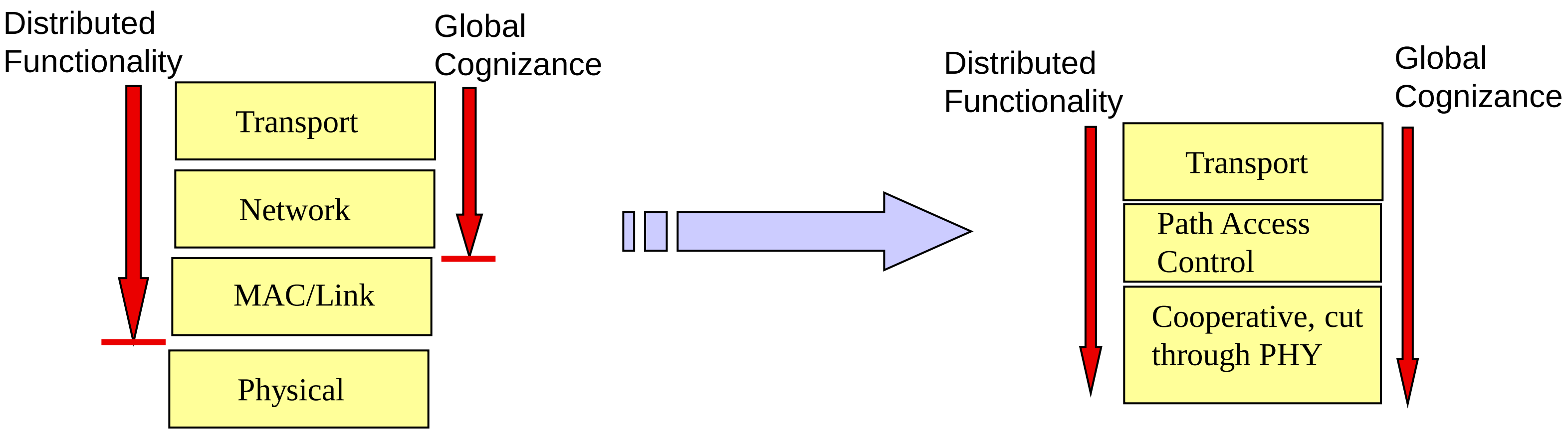


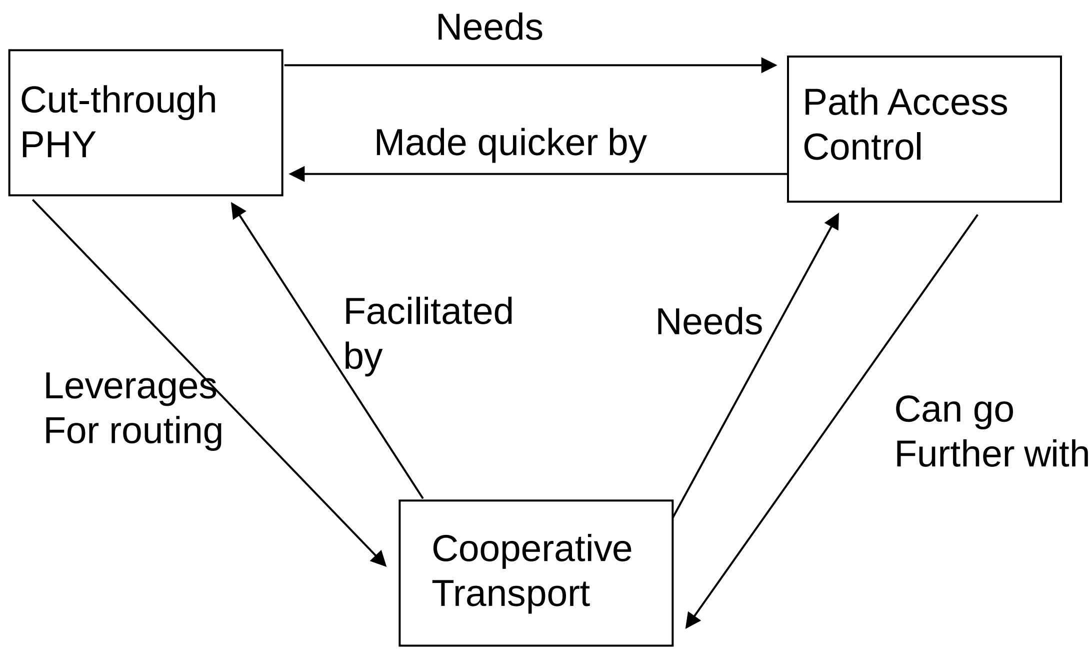




R. Ramanathan, F. Tchakountiou, "Channel Access over Path Segments for Ultra-low-latency MANETs," *IEEE MILCOM, 2007*

Architecture: Whole > Sum of Parts





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MAC: TDMA vs CSMA/CA

Feature	(Spatial reuse) TDMA	CSMA/CA
Reserved Access	Excellent support	Poor support
Admission control	Easy to do	Hard to do
Long delay links	Supportable, with work	Poor fit, CS not possible
Efficiency at high load	High	Low
Synchronized operation	Requires slot/frame sync	Not required
Control complexity	Complex without centralized control	Peer-to-peer natural
Mobility	Induces re-scheduling overhead	Not a problem
Bursty traffic	Poor support in most protocols	Naturally adapts

A new approach to media access is required that combines the strengths

Sync-less Impromptu TDMA

- Floor acquired like in CSMA/CA with a handshake, but the access rights are implicitly periodic (a slot "chain")
- Slots are relative to the handshake, so no sync required
- Benefits
  - Reserved channel access based on traffic demand
  - Signaling and control overhead less than that of 802.11 or TDMA
  - Conceptually simple, and much easier to implement than TDMA while providing behavior similar to TDMA
  - Well-suited to "linkless" architecture (path-based/cooperative access)
- Other similar work, and novel MAC proposals exist: Much room for improvement, and adaptation to a "link-less" architecture

G. Jakllari, M. Neufeld, R. Ramanathan, "SITA: Sync-less Impromptu Time Divided Access." *IEEE Milcom,* 2009.
G. Jakllari, M. Neufeld, R. Ramanathan, "A Framework for Frameless TDMA using slot chains", *IEEE MASS* 2012.
S. Singh, P. Acharya, U. Madhow, E. Royer, "Sticky CSMA: Implicit Synchronization in Mesh Networks, *Ad Hoc Networks,* Aug 2007

Summary

- The way MANETs are currently architected is a legacy of the wired “link-centric” thinking and is inefficient
- Holistic analysis of real-world networks indicates better returns if we invest in lower layers first
- Architectural elements for the next generation
  – Cooperative communications
  – Relay-oriented physical layer, with cut-through relaying
  – Closing the gap between ideal & existing MAC efficiency/ robustness
  – Gradient and backpressure routing, beamforming, and others
- New ideas ensconced in radically new architecture

